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FIFTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY MARCH 1-7, 2000

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Sheilda L. Bryner, Editor

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U. S. Department of Commerce
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Technology Administration
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INTERNATIONAL ROUND ROBIN TESTING WITH ISO5660 CONE CALORIMETER (INTERIM ANALYSIS REPORT)

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ABSTRACT

An interlaboratory trial has been carried out on the ISO5660 Cone Calorimeter by 19 laboratories from Asia-Oceania, American Continent and Europe as a CIB W14(Fire) subprogram. The project features cooperation of fire laboratories with only weak connection, and the methodology to improve reproducibility of reaction -to-fire tests among laboratories without strong face-to-face cooperation framework. The interim result of the analysis with the reported data suggest encouraging prospect to achieve a reasonable reproducibility by using common reference heat flux gage, and common calibration samples.

Keywords: Cone Calorimeter, round robin

INTRODUCTION

Introduction of the oxygen consumption principle and popularization of heat flux measurement in fire research during 1980's are among the most important changes in fire testing technologies. These have enabled practical and direct measurement of the most important index for fire hazard assessment and the direct index representing the intensity of fire exposure. These measurement technologies are a central vehicle to promote engineering approach in material fire safety through producing input data for fire models and evaluating the validity of fire models. Most of the recent ISO reaction-to-fire tests already adopt either the oxygen consumption principle or the heat flux measurement.

The oxygen consumption principle is, however, much more sophisticated than such conventional fire measurements as thermocouples or optical density. Also heat flux measurement using heat flux gage is believed to be sensitive to its maintenance and other conditions. There are many fire laboratories not very familiar with qualified use of these measurements, and it is believed that there are still many technical aspects left unsolved for the promotion of practical use and scientific application of these measurements. Many laboratories in Europe, and Northern America have already been involved in international interlaboratory calibrations partly in view of such problems[1].

Since around the beginning of 1990's, there has been significant spread of modern fire test methods and research-oriented fire test facilities to outside Western Europe and Northern America. This trend reflects the increase of fire risk through industrialization and that of the interest in fire safety science and engineering especially in newly industrialized countries. However, many of the new fire laboratories do not yet have direct access to international fire research and technical information, and there is still basic difficulty in the qualified use of modern fire tests in many of the new fire laboratories. In view of the recent increase of the Cone Calorimeters in Japan since around 1993, a round robin with the Cone Calorimeter was initiated in 1994 under the coordination by Building Research Institute, Ministry of Construction, Japan. Several fire laboratories outside Japan joined this round robin as has been reported elsewhere[2]. There are, however, still many laboratories including CIB and CIB W14(Fire) members, who do not have a forum for this kind of activity. For further promotion of qualified use of heat release and heat flux measurement in such laboratories isolated from preceding laboratories or districts, it was felt necessary to develop some comprehensive procedure and possibly a network to improve reproducibility and establish confidence[3]. An extension of this interlaboratory cooperation was planned in order

- to include newer Cone Calorimeter users

- to ensure that there is a substantive number of laboratories especially in Japan and the newly industrialized districts intimately familiar with conducting tests in the Cone Calorimeter

- to enable recommendations and proposals to be made on the protocol set forth in the Cone Calorimeter standards and verify that these are consistent with operating experience

- to promote technical communication among fire laboratories in different regions.

This extended program was proposed as a CIB W14 sub-group programme, and was discussed at the CIB W14 Plenary meeting at Espoo, Finland, in January 1995. The objectives and scope of the interlaboratory trials are:

- to improve the skill and of fire growth measurements at fire laboratories, especially in newly industrialized countries and developing countries

- to further develop technical guidelines for fire growth measurements, especially for heat flux and rate of heat release

- to derive methods and protocols to improve reproducibility of heat release and heat flux measurement among fire laboratories

- to promote technical communication among fire laboratories in different regions.

This series of interlaboratory trials reflects the experience and lessons from the previous Cone Calorimeter interlaboratory trials[2], and has tried to adopt better defined procedures including use of reference heat flux gages calibrated against a single radiation source, use of single calibration sample and others.

Invitation for participation in the interlaboratory trials was first circulated to CIB W14 members in July, 1995 and the interlaboratory trials were started in November 1995. Non-CIB member laboratories who were interested in the participation were also invited to the program. 19 laboratories from 12 countries and districts finally participated in the Cone Calorimeter interlaboratory calibration. This paper intends to report the summary procedure of the program and the statistical analysis of the test data submitted in time.

INTERLABORATORY TRIALS

Participants

The 19 fire testing laboratories shown in Table 1 participated in the interlaboratory trials.

Table 1 Participating laboratories

Country/ District	Organization	Country/ District	Organization
Australia	●CSIRO Division of Building, Construction and Engineering	New Zealand	●Building Research Association of New Zealand
Canada	●Institute for Research in Construction, National Research Council	Poland	●Institute of Natural Fibres
China	●Institute of Building Fire Research, China Academy of Building Research ●State Key Laboratory of Fire Science, University of Science and Technology of China	Slovakia	●State Forest Products Research Institute
France	●Centre de Recherche et d'Etude sur les Procedes d'Ignifugation des Materiaux	Taiwan	●Architecture and Building Research Institute
Italy	●Central Institute for Building Industrialization and Technology, National Research Council ●L.S.F. Laboratorio di studi e ricerche sul fuoco	UK	●Department of Materials, Queen Mary and Westfield College, University of London
Japan	●Building Research Institute ●Forestry and Forest Products Research Institute ●Hokkaido Forest Products Research Institute ●Research Institute of Marine Engineering ●Japan Electric Cable Technology Center, Inc.	U.S.A.	●Forest Products Laboratory USDA- FS ●ATLAS Electric Devices Company

The participants will be identified only by alphabetical characters in this report. Dr.M.L.Janssens, then ISO/TC92/SC1/WG5 convener, Prof.M.Kokkala, CIB W14(Fire) Coordinator, Dr.V.Babrauskas, Prof. W.K.Chow and Dr.J.H.Fangrat served as advisers for this project.

Secretariat and Correspondence

Building Research Institute, Ministry of Construction, offered the secretariat. The role of the secretariat was to plan the project, to arrange specimens and instructions, and to make correspondence with participants. M.Yoshida made correspondence with Japanese participants, and A.Marchal, then STA Fellow at BRI, and Y.Hasemi, then BRI Head of Fire Safety Division, made correspondence with foreign participants.

Procedure

The interlaboratory trials were divided into the following stages:

1) Questionnaire on the apparatus

Questionnaire on the apparatus and its operation was sent to those who were interested in the participation(APPENDIX).

2) Calibration of heat flux gages

The project was initiated with the calibration of the heat flux gages of the participating laboratories with 11 reference Schmidt-Boelther gages which had been calibrated against a single radiation source. The heat flux gages were circulated in the participants, and each laboratory compared its heat flux gage for the determination of heat flux level with at least one reference heat flux gage. All reference heat flux gages returned to the secretariat were recalibrated. No notable difference from the initial calibration was found with each reference heat flux gage.

3) Calibration of heat release rate

Calibration of heat release rate was made with methanol. The tray was delivered from BRI to each participant. Choice of methanol as the common calibration specimen for heat release rate, in spite of the specification of the use of pure methane in the ISO5660 current draft, was because

- pure methane is difficult to obtain in many countries including some of the participating countries. Combustion heat of methane is generally so sensitive to its purity that its avoidance seemed to be reasonable to prevent confusion in the calibration.

- heat release rate of the methanol is comparable with that of most of the materials used as specimens of the present interlaboratory trials.

Although the secretariat offered diagnosis, relatively few laboratories reported the test result to the secretariat. Possible problems with heat release measurements at each participant were reported to the reporting laboratories for the improvement of the operations.

4) Preliminary round robin with a thick black PMMA specimen

Before dealing with different specimens, measurement of heat release rate for 25mm thick black cast PMMA was conducted for the diagnosis of the general performance of the machine of each participant. The black thick cast PMMA was chosen as a highly reproducible material whose properties are simple and combustion behavior is stable. Also black thermally thick PMMA is believed to be appropriate for the diagnosis on various aspects of burning behavior including time to ignition, heat release rate before the penetration of the specimen by thermal wave and total heat release rate. Three samples of black cast PMMA were sent to each laboratory. All the specimens were prepared using products from a single lot directly shipped by a manufacturer. Results and anticipated troubles of the apparatus of each laboratory was reported to each participant for the possible improvement of the operation and the apparatus.

5) Final round robin

Round robin was conducted using 8 different materials as specimens. During the round robin, frequent communication and information exchange was conducted between the secretariat and participants and sometimes among participants. Because of this active interaction, it is believed that detail of the operation at most of the participants was renewed and improved frequently. This may make the analysis of the data rather difficult, but such communication should have been quite effective for the improvement of measurement skill of laboratories which are otherwise isolated from international technical information on testing.

Specimens

During the last stage of the interlaboratory trials, the following materials prepared for the testing were chosen as specimens.

A)PMMA sheet, transparent, 10mm thick, density 1180kg/m^3(to be abbreviated as PMMA)
B)Medium Density Fiber Board, untreated(natural wood color), 12mm thick(MDF)
C)Polyvinyl Chloride Coated Steel Plate, black, 0.6mm thick, average density 6870 kg/m^3 (VCSP)
D)Gypsum board, covered by paper sheets on both sides, 9.5mm thick(GB)
E)Fiberglass-reinforced Polyisocyanulate(FGPC)
F)Polystyrene Foam(PS)
G)Polyurethane Foam(PU)
H)Fire Retardant Wood(FRW)

These specimens cover most types of combustible materials common in construction in the light of composition, dynamic combustion behavior and fire safety performance. PMMA was chosen as a representative noncharring stably-burning material, MDF was chosen as a wood-based industrial charring material, Polyvinyl chloride coated steel plate was to represent a thermally thin lined material with a sharp peak of heat release rate. Gypsum board with wall paper was to represent a thermally thick line material with a sharp peak of heat release rate. Gypsum board was chosen also to evaluate the quality and influence of conditioning of specimens as the fire performance of gypsum board is believed to be sensitive to the moisture. Fiberglass-reinforced polyisocyanulate, polystyrene foam and polyurethane foam were chosen to represent different burning behaviors of polymers. Although originally only the materials A) through D) were chosen and sent to the participants, analysis of the test results from the participants at this phase suggested that the problems anticipated at the preliminary round robin with black PMMA had not been well resolved. Also since some participants suggested needs of testing of foamed plastics, the secretariat arranged specimens of fiberglass reinforced polyisocyanulate, polystyrene foam, polyurethane foam and fire retardant wood and sent again to the participants. The materials A)~D) and E)~H) were tested at different period.

All specimens of each material were arranged by BRI using the products from a single lot directly shipped by the factory. 12 replicas of each material were sent to each participant.

TEST RESULTS AND COMMENTS

Table 2 is a summary of the test data delivery from participants. Although 19 laboratories participated, it was not able to open finally the data file from one laboratory. The table shows a summary for the rest of participants. Although most of the participants delivered data on the black PMMA, MDF, GB, PMMA, PS, PU and VCSP, relatively few participants reported data on methanol, and only one laboratory reported the data on FRW. The missing of the data on FRW at most of the laboratories is probably because the heat release rate from this material was too weak to measure.

Diagnosis with Black Thick PMMA

From previous round robins with the Cone Calorimeter and laboratory experiences, typical "symptoms" of test results can be summarized in conjunction with their possible causes as shown in Table 3.

Calibration of heat flux gages and heat release measurement with methanol conducted before the round robins actually aimed at preventing possible troubles with heat flux gages and oxygen analyzer among such common troubles with the Cone Calorimeter.

Table 2.

HEAT FLUX 50kW/m2 Test Number

LAB.ID	BLACK PMMA	METHANOL -50	METHANOL -100	METHANOL -150	METHANOL -200	FGPC	FRW	GB	MDF	PMMA	PS	PU	VCSP
A	1	1	2	1	1	3		3	3	3	3	3	3
B	1	1	1	1	1	3	3	3	3	3	3	3	3
C	1					3		3	3	3	3	3	3
D	1					3		3	3	3	3	3	3
E	1					3		3	3	3	3	3	3
F	1	1	2	1	1	3		3	3	3	3	3	3
G	1					5		3	3	3	4	3	3
H	1	1	1	1	1	3		3	3	3	3	3	3
I	1					3		3	3	3	3	3	3
J	1							3	3	3			3
K	1					3		3		3	3	2	3
L	1					3		2	2	2	2	3	3
M	1	1	2	1	1	3		3		3	3		3
N						3		3	3	3	3	3	3
O	2												
P	2	1	2	1	1	6		3	3	3	3	3	3
Q	1					3		3	3	3	3	3	3
R	1								3	3			3

HEAT FLUX 30kW/m2 Test Number

LAB.ID	BLACK PMMA	FGPC	FRW	GB	MDF	PMMA	PS	PU	VCSP
A	1	3		3	3	3	3	3	3
B	1	3	3	3	3	3	3	3	3
C	1			3	3	3	3	3	3
D	1	6		6	3	3	3	3	3
E	1	3		3	3	4	3	3	3
F	1	3		3	3	3	3	3	3
G	1	5		6	3	3	3	3	6
H	1	6		3	3	3	3	3	3
I	2	3		3	3	3	3	3	3
J	1			3	3	3			3
K	1	3		3		3	3	3	3
L	2	3		3	3	3	3	3	3
M	1	3		3		3	3		3
N		3		3	3	2			2
O	1								
P	1	3		6	3	3	3	3	6
Q	1	3		3	3	3	3	3	3
R	1				3	3			3

Table 3 Typical troubles with Cone Calorimeter and Resulting Symptoms

	troubles	symptoms in indicated data			remarks
		time to ignition	peak heat release rate	total heat release rate	
Heat flux gage	indicated heat flux higher than reality	too long	too low		Heat flux gage of each laboratory was to be calibrated against common reference heat flux gage.
Oxygen analyser	preset initial O_2 concentration higher than reality		too high	too high	Actual ambient O_2 concentration in laboratory can be fluctuated from default O_2 concentration.
Duct flow velocity	excessively high	too long	too low		Excessively high flow rate often causes convective cooling of the specimen surface.Excessively high flow rate often causes convective cooling of the specimen surface. This effect is believed to be more influencial to time to ignition than heat release rate.
Specimen holder	thermal insulation or substrate behind specimen		too high		Insulation behind specimen should not influence time to ignition nor heat release rate before the penetration of the specimen by thermal wave.
Preset area of burning surface	larger than reality		too low	too low	Preset value of surface area of each laboratory was reported to the secretariat.
A/D transform board	indicated time interval longer than reality			too high	
Data processing	smoothing		too low		

After the preliminary round robin with black thick PMMA, some analysis was was made on the submitted data for diagnosis of the apparatus of the participating laboratories. Figures 1(a) - (d) are a summary of the data on the heat flux level 50kW/m^2. The alphabetical characters denote the participants. While the data are rather scattering in Figures 1(a)-(c), total heat release rate is clearly correlated positively with peak heat release rate. Positive correlation between peak and total heat release rates were also observed at the heat flux level 30kW/m^2. This suggests a need of the calibration of oxygen analyzer, while the data do not show any sign for the inconsistency in the measurements of heat flux and duct flow. Diagnosis on the black thick PMMA data also revealed troubles of specific laboratories. For example, time to ignition reported from laboratory I was rather unstable in that the time to ignition for 50kW/m^2 was very short and that for 30kW/m^2 was very long. Through communication between the secretariat and the laboratory, this was finally attributed to the control of duct flow rate. The weak peak heat release rate at laboratory R was attributed, at least partly, to the smoothing of the test data. Signs for other troubles were recognized at each participant, which are summarized as:

Improper calibration of heat flux gage: F, K
Duct velocity: F, I, K
Wrong preset of burning surface area: A, C, P

Heat release rates on black PMMA reported from those laboratories that had joined the heat release calibration with methanol seem to be within narrow range around the average if data calculated with wrong surface area is properly adjusted. This is believed to endorse importance of the calibration of heat release rate using some appropriate material for the maintenance of Cone Calorimeter. Such information was delivered to each participant before the round robin with commoner building materials.

Final Round Robin Results

Figure 2 - 8 are summaries of the correlations for the materials used for the final round robin summarized in similar way with the preliminary round robin.

The peak and total heat release correlations for some of the specimens during the first phase of the round robin, e.g. gypsum board at 30kW/m^2 heat flux level(Figure 5(h)), indicate a sign for the diverse definition of the ambient O_2 concentration which had been already pointed out at the preliminary round robin. At most of the participating laboratories, gypsum board was the the specimen to start with at this stage of round robin. Weaker correlation between peak and total heat release for other materials, except for a few laboratories, suggests improvement of the operation of oxygen analyzer during this stage of the round robin. Reported total heat release on PMMA very consistent among the participants(Figure 2(d),(g)) seems to endorse the improvement of the oxygen analyzer before and during the round robin process. Results on the materials tested in the second phase, FGPC, PS, and PU, show only very weak correlation between the peak and total heat release.

The significant scattering of the data for gypsum board at 30kW/m^2 heat flux level(Figure 5(e),(g)) should be noteworthy. Performance of gypsum board, especially at weak heat flux level, is believed to be the most sensitive to moisture among the materials tested in this round robin. This scattering may indicate the diverse quality of conditioning among the laboratories.

Results on Polystyrene at 30kW/m^2 (Figure7(a)) are divided into two groups, one with higher heat release rate and shorter time to ignition and another characterized by very long time to ignition(laboratories A,I and N). This material causes surface melting and degradation prior to the ignition when it is exposed to relatively weak external heating. Such surface degradation is believed to decrease the incident heat flux to the surface and delay the ignition. Laboratories A and I are "slow" laboratories in the sense that time to ignition reported from them was generally longer than others. Results from these two laboratories far from others are attributed to the start of melting before the ignition.

From general observation of the time to ignition, it can be concluded that laboratories F and I are "slow" laboratories and E and K are "fast" laboratories. Time to ignition reported by laboratories E and F was sometimes very far from others, while peak heat release rate and total heat release rate reported from these laboratory are generally around the average of all participants. This suggests that laboratory E and F rely on different definitions of ignition from all other participants. Data on polystyrene at 30kW/m^2 from F fallen into the "faster" group(Figure 7(e), (g)) may support this explanation for the general features of the data from laboratory F. Time to ignition reported from laboratory E at the second phase(Figures 6, 7, 8) became somewhat closer to average than at the first phase. This may indicate conscious or unconscious change of the definition of ignition at this laboratory caused by the diagnosis on the results at the first phase. On the other hand, peak heat release rate from laboratory I was generally lower than others, which suggests the heat flux gage output of this laboratory higher than the reality. The duct flow velocity of this laboratory, estimated from its duct pressure data, was found to be one of the lowest among the participant, which is believed to lead rather to faster ignition.

Lessons from the Interlaboratory Trials

This project revealed the importance of interlaboratory calibration of heat flux gages and heat release measurements and technical communication among laboratories for the reproducible operation of the Cone Calorimeter. Although there was significant scattering of the data at the beginning of the project, those laboratories active in the pre-roundrobin calibrations and communications with the secretariat throughout the project, such as C,D,G, and L, demonstrated consistent tests results during the final round robin although all these four laboratories are geographically isolated on the globe and are believed to have had few contact with each other before this project. Active correspondence is obviously a sign for the strong interest and the skill of the person in charge. The experience with this project also suggests importance of internal communication in laboratory. From communication between participants and the secretariat, it has been often felt that diagnosis of the test results and suggestions from the secretariat was not forwarded to those who actually operated the Cone Calorimeter. At some laboratories, it seemed that corresponding scientist ran the apparatus by himself/herself; such laboratories generally were able to improve the operation smoothly. Perhaps these will apply not only to the Cone Calorimeter but also to different types of modern fire tests and measurements. In that sense, interlaboratory cooperation is believed to be essential for the promotion of experimental fire research.

Acknowledgments

The coordinators of the round robin would like to acknowledge efforts of Dr.A.Marchal as a secretary during his stay at BRI, and technical support of Dr.M.L.Janssens, Southwest Research Institute, then ISO TC92/SC1/WG5 convener, who contributed valuable advices on the project and offered updated drafts of the ISO5660 Cone Calorimeter for this program.

This project has been helped by the generous contributions of numbers of organizations and individuals in various ways.

Participation of international experts in the international business meeting for the project in Tokyo, October 1995, was financially supported by the TOSTEM Foundation, Japan. Its meeting place was offered and arranged by the Association of International Communication for Building and Housing(currently International Institute for Buildings and Housing). Part of the specimens were offered by the Association of Fire Protective Materials Manufacturers. The Association and Architectural Institute of Japan offered arrangement of domestic working meetings. The stay of Dr.Marchal at Building Research Institute was essentially supported by the STA Fellowship through arrangement by Science and Technology Agency, JRDC and JISTEC. Prof.T.Wakamatsu, Science University of Tokyo and Building Center of Japan offered admiministrative assistance for the extension of his stay. The coordinators wish to acknowledge these supports which helped ensure the pursuance of the project.

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APPENDIX

CONE CALORIMETER ROUND ROBIN PRELIMINARY QUESTIONNAIRE

Name of Laboratory:________________________________

Manufacturer of your Cone Calorimeter: ________________________________

Product Name of your Cone Calorimeter: ________________________________

Manufacturer and Product Style(if available) of Heat Flux Gage:____________________

Cone/Specimen Environment:________________________________

Please describe how many out of the four vertical sides of the Cone/specimen area are covered with permanent wall, glasses or doors.

____

____

Gas Analyzer:	Manufacturer	Product	Range(%)	Estimated Delay of Response(sec)
Oxygen				
Carbon Monoxide				
Carbon Dioxide				

Calculation of heat release rate(please tick)

- ☐ software prepared by the manufacturer, equations unknown
- ☐ software prepared by the manufacturer, equations known(please attach documents describing the equations if available)
- ☐ software prepared by __________________(please attach the equations if possible)
- ☐ availability of smoothing(please attach the concept if available)

Treatment of the initial condition of O_2 concentration in the calculation of heat release rate

- ☐ assumed as 20.95%
- ☐ average for _____seconds until the start of the test

Laboratory conditions:

size of the room for the Cone Calorimeter: ________m^2

installation of air conditioning/forced ventilation etc:

☐ air conditioning during test(if yes, please note the approximate room temperature and humidity during tests)

☐ ventilation only

Maintenance:

Is your Cone Calorimeter run always by specific person(s)?

____

Is the heat flux gage used for your Cone Calorimeter calibrated periodically against any radiation source or virgin heat flux gage?

____

____

____

____

Conditioning of specimens:

Do you condition specimens for your Cone Calorimeter before each test? If so, please describe the temperature, relative humidity and the term for the conditioning.

____

____

____

____

Experience in the use of Cone Calorimeter:

In what year did your laboratory introduce the Cone Calorimeter equipment, and how long does your laboratory have used it?

____

How many times a year does your laboratory use the Cone Calorimeter equipment?

____

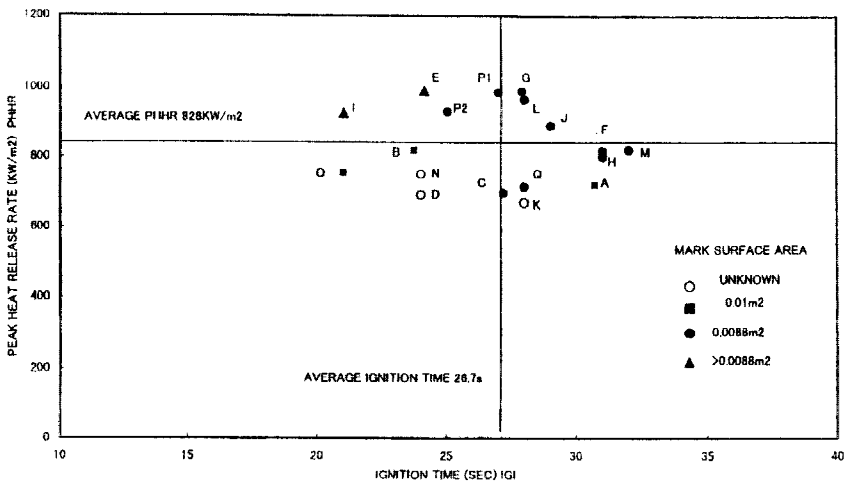

Figure 1(a) black PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m² (Preliminary round robin)

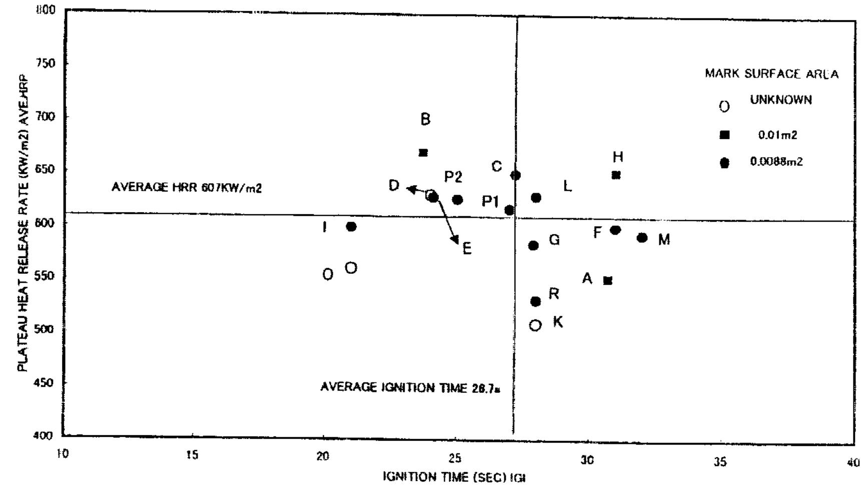

Figure 1(b) black PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m² (Preliminary round robin)

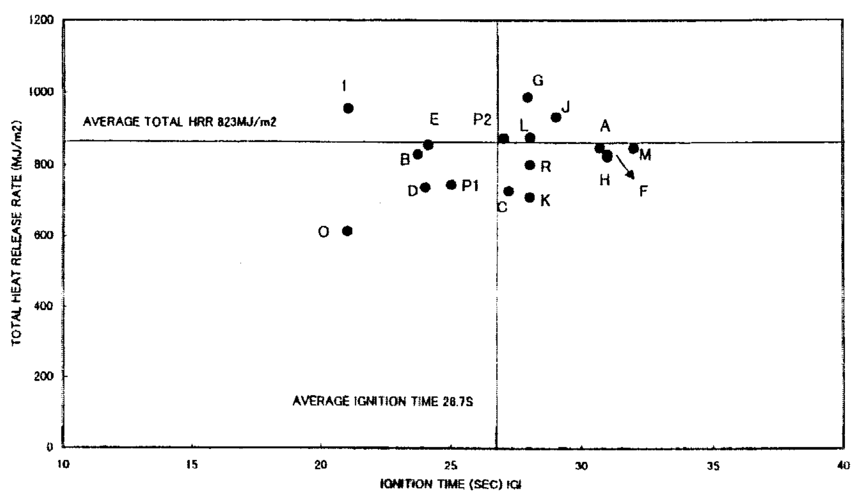

Figure 1(c) black PMMA, Time to ignition vs. Total heat release
Heat flux level: 50kW/m² (Preliminary round robin)

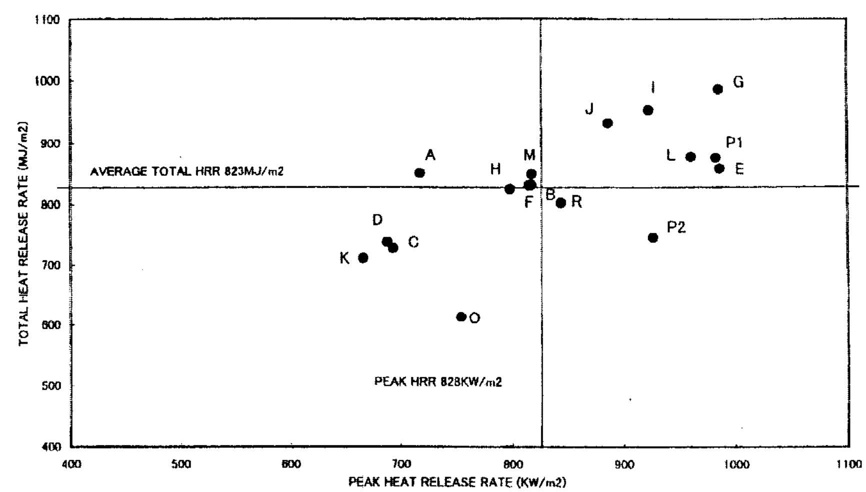

Figure 1(~~b~~d) black PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m² (Preliminary round robin)

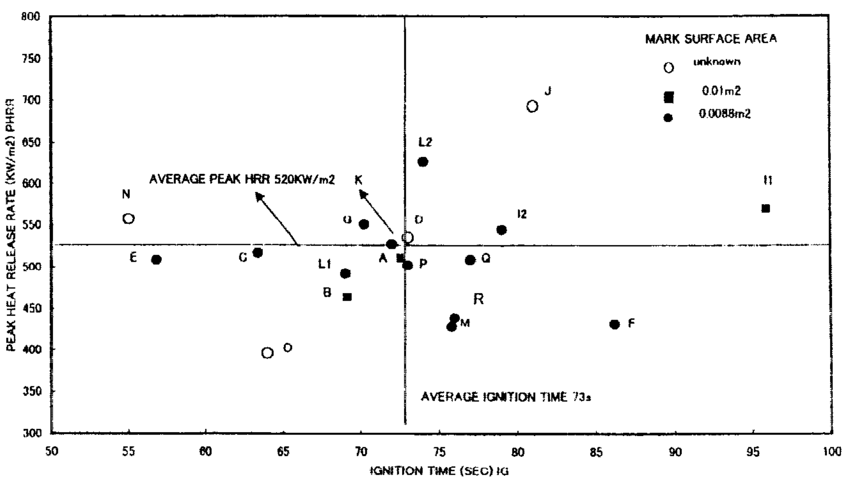

Figure 1(e) black PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m² (Preliminary round robin)

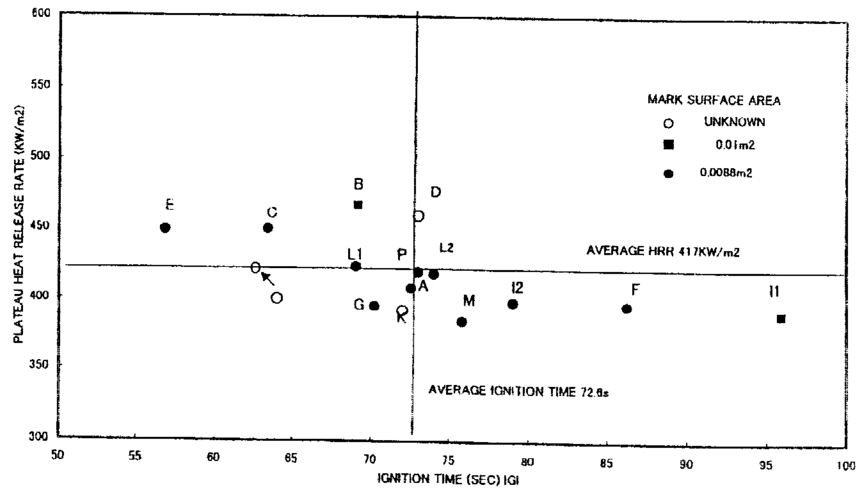

Figure 1(f) black PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m² (Preliminary round robin)

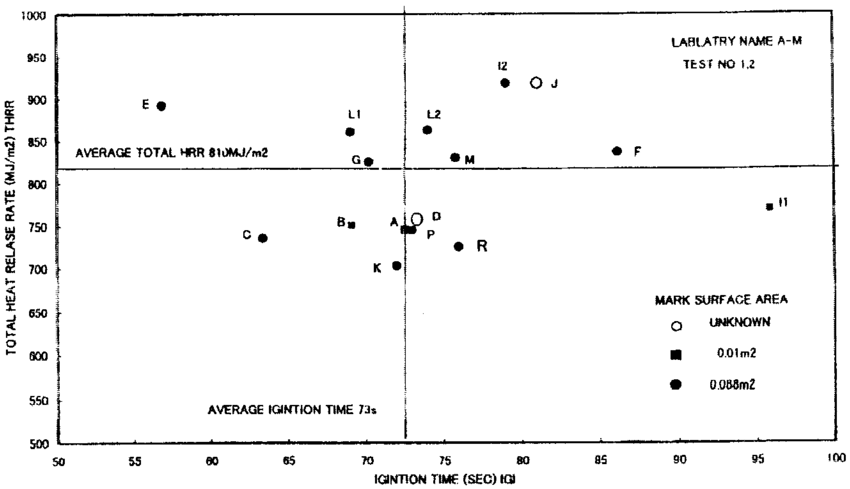

Figure 1(g) black PMMA, Time to ignition vs. Total heat release
Heat flux level: 30kW/m² (Preliminary round robin)

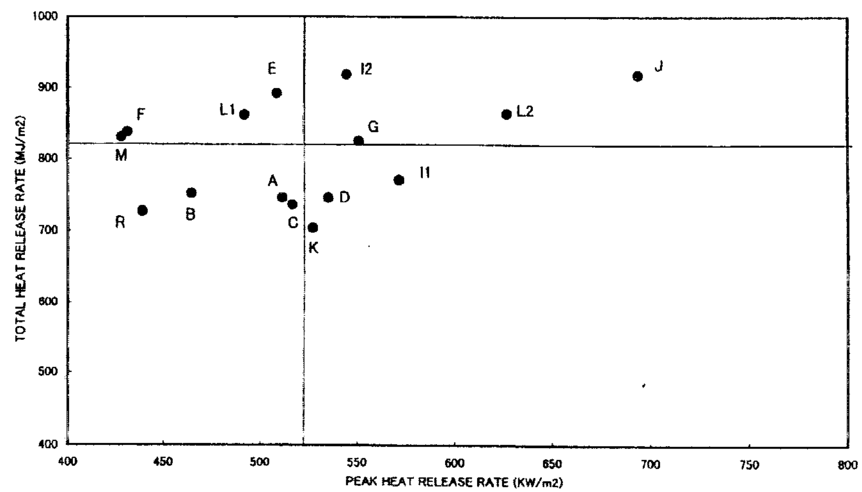

Figure 1(h) black PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m² (Preliminary round robin)

Figure 2(a) PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 2(b) PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

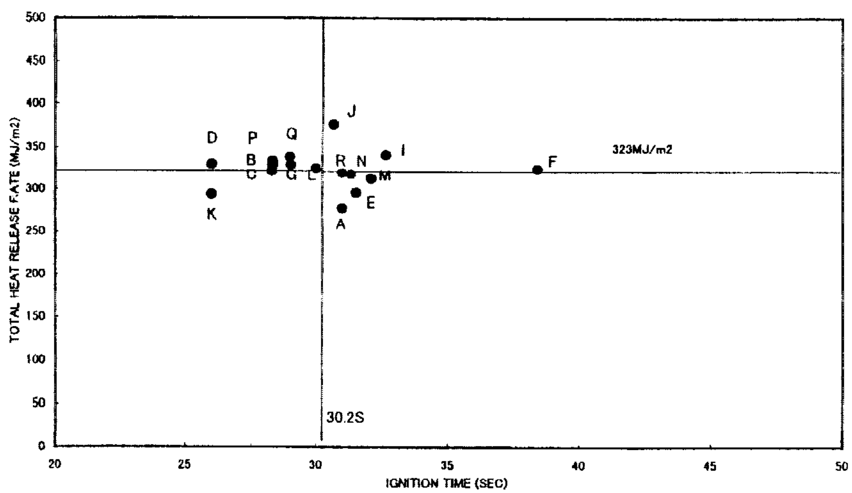

Figure 2(c) PMMA, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

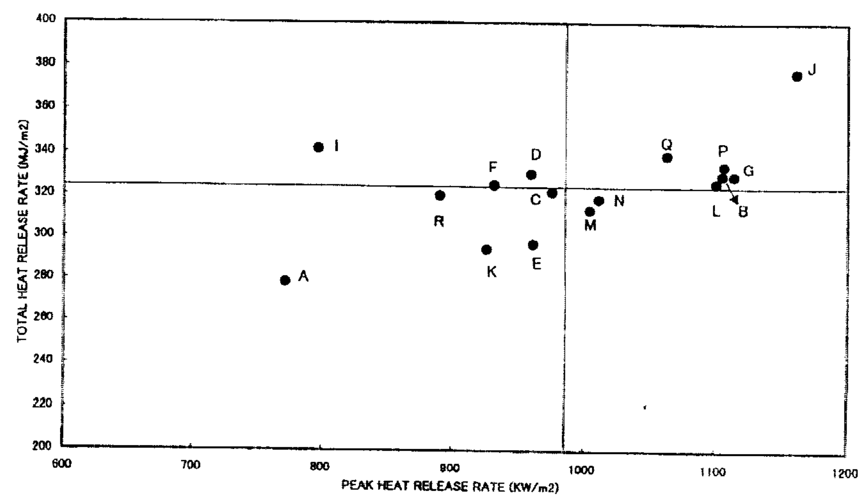

Figure 2(b) PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

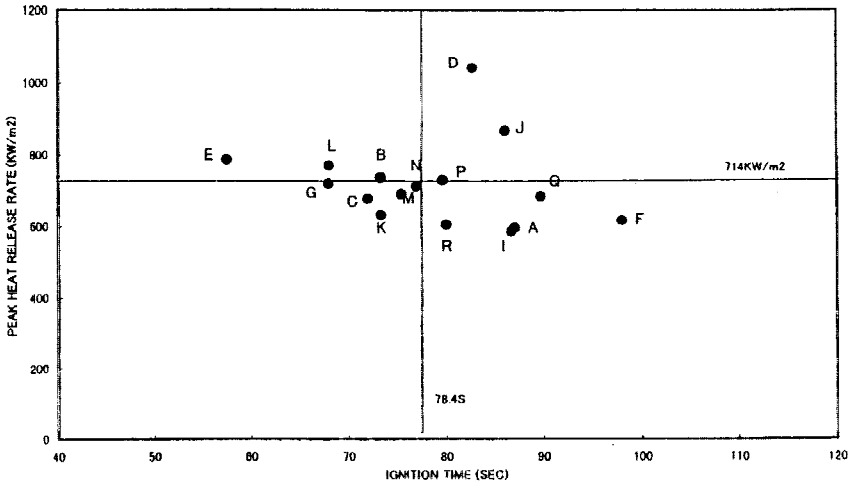

Figure 2(e) PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 2(f) PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

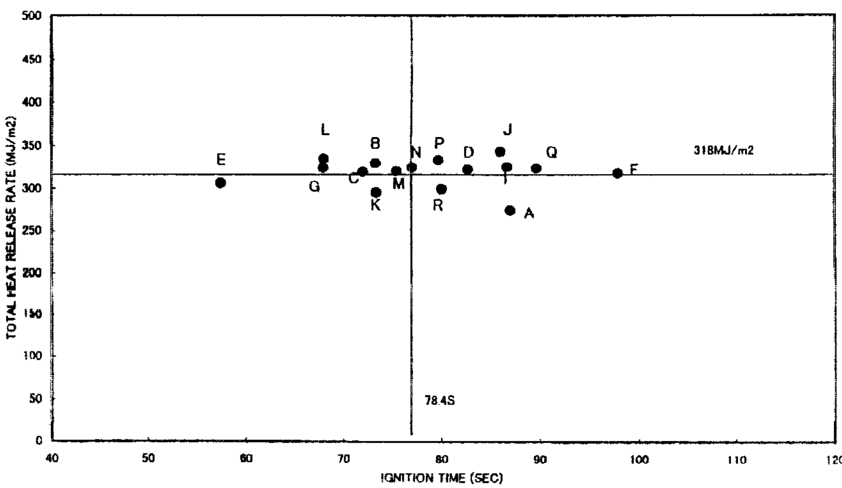

Figure 2(g) PMMA, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

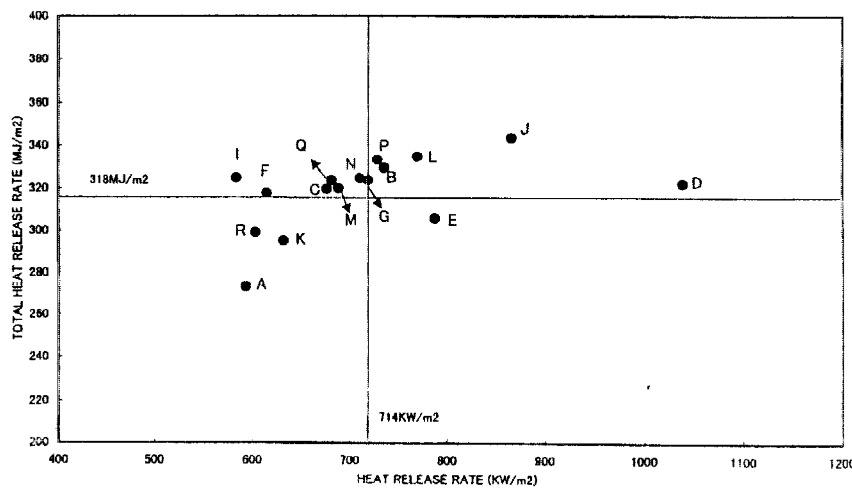

Figure 2(h) PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

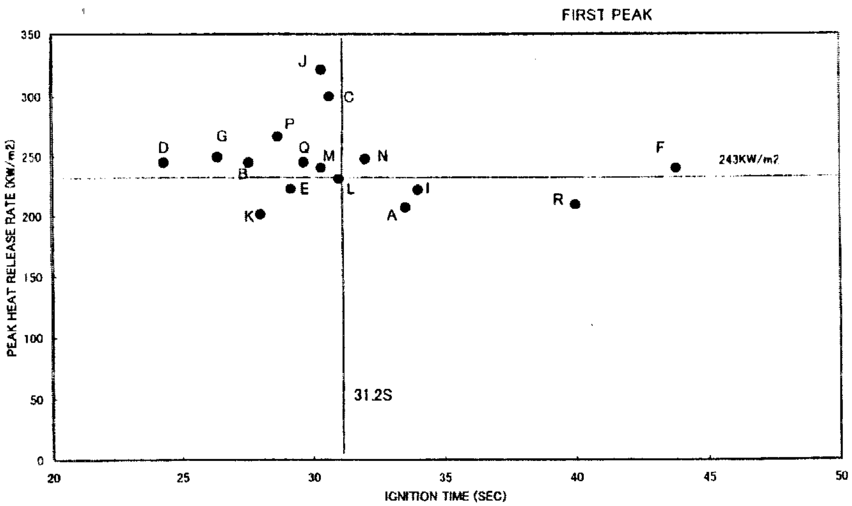

Figure 3(a) MDF, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 3(b) MDF, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

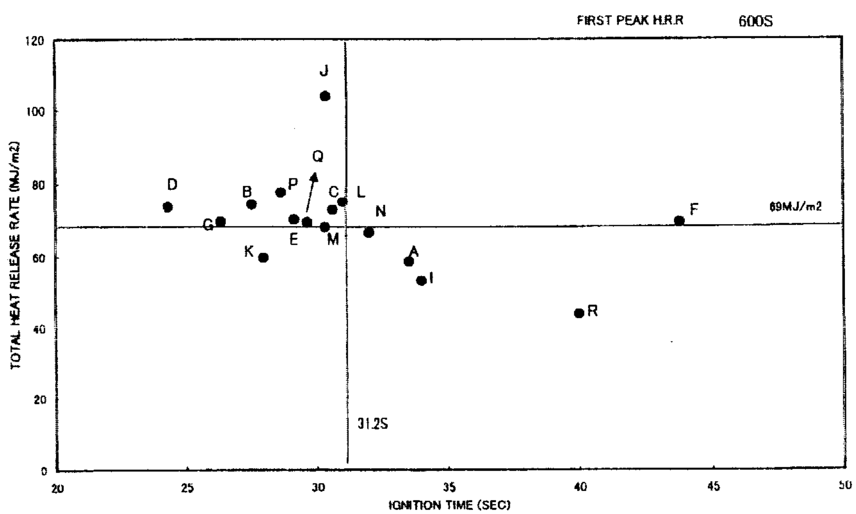

Figure 3(c) MDF, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

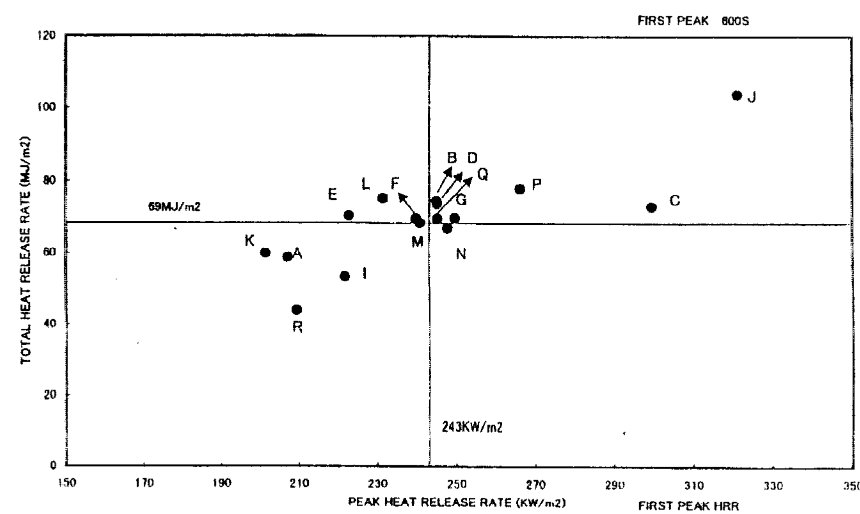

Figure 3(d) MDF, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

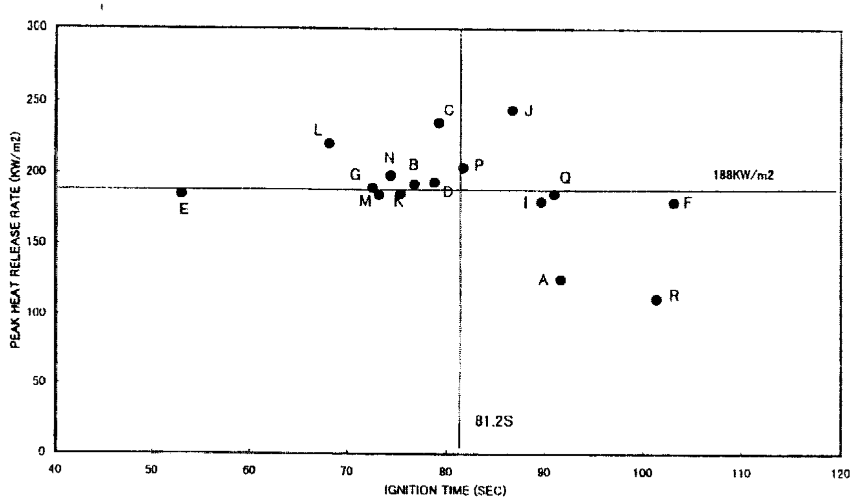

Figure 3(e) MDF, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 3(f) MDF, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

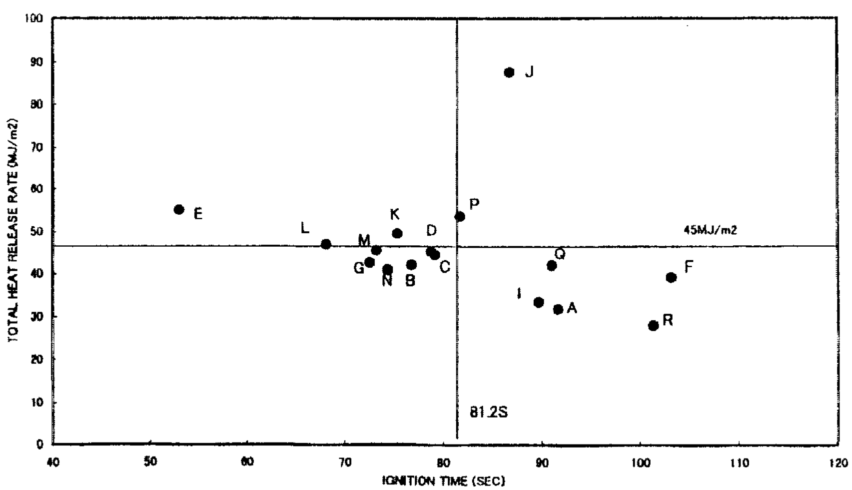

Figure 3(g) MDF, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

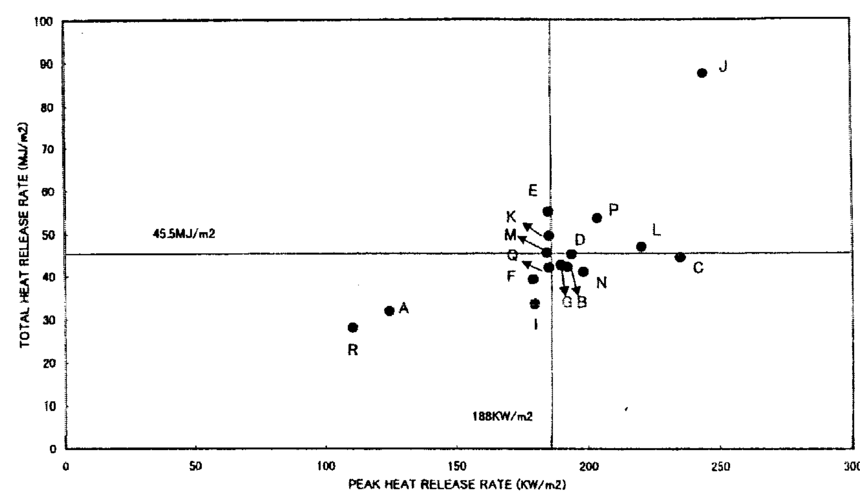

Figure 3(h) MDF, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

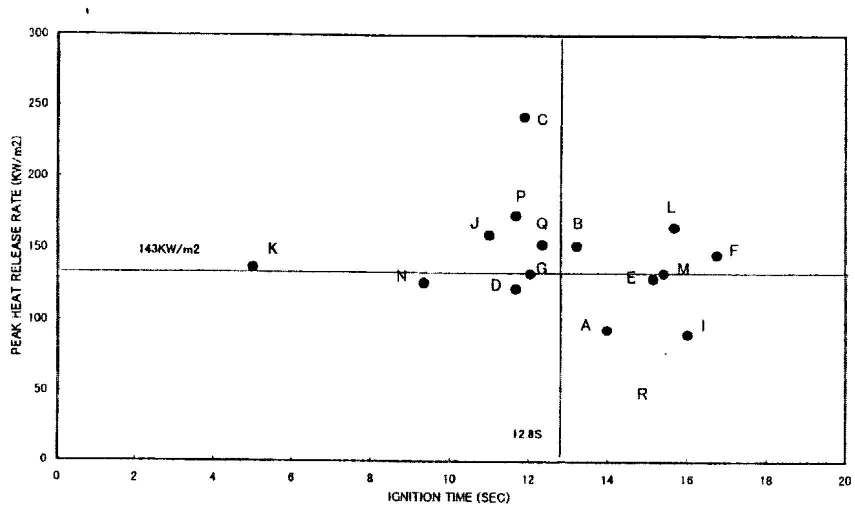

Figure 4(a) VCSP, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 4(b) VCSP, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

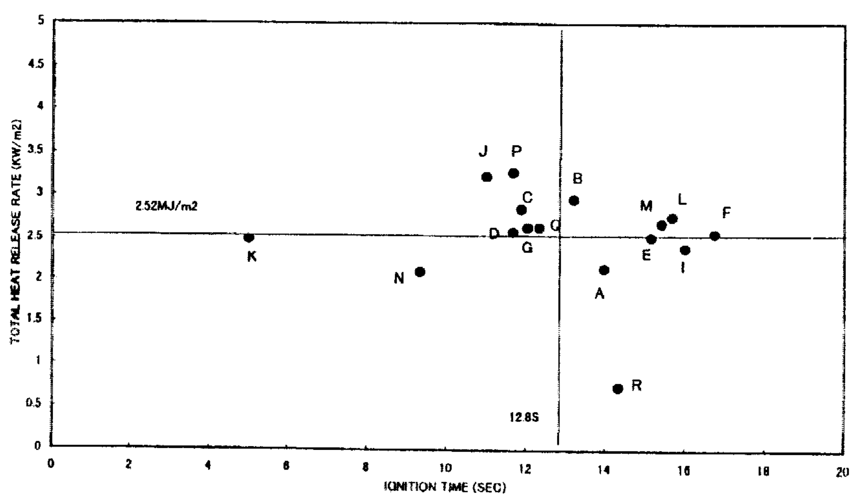

Figure 4(c) VCSP, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

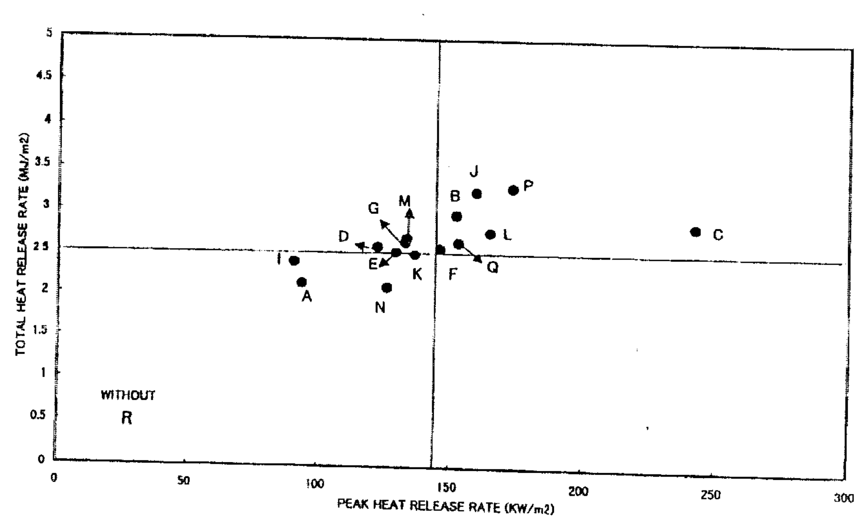

Figure 4(d) VCSP, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

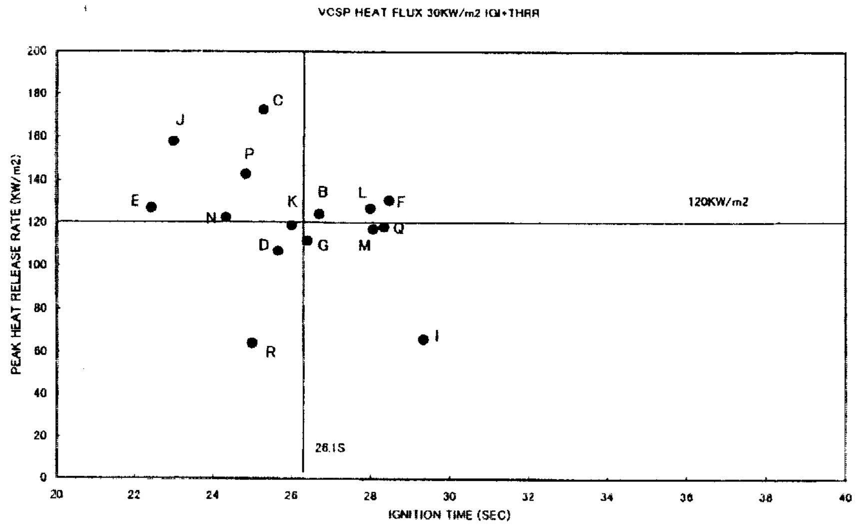

Figure 4(e) VCSP, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 4(f) VCSP, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

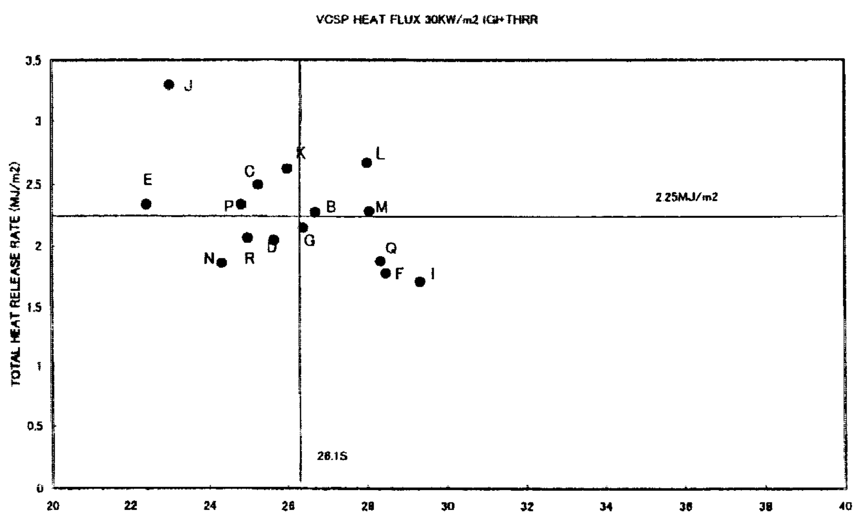

Figure 4(g) VCSP, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

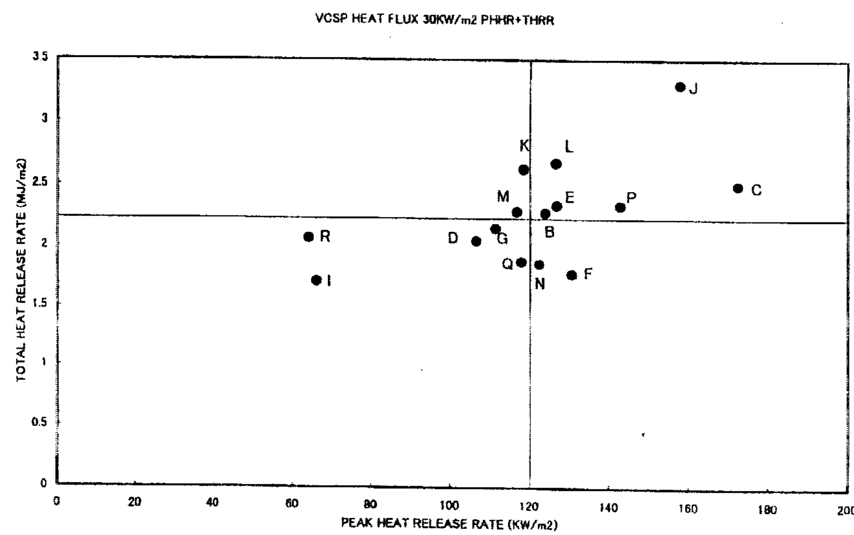

Figure 4(h) VCSP, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

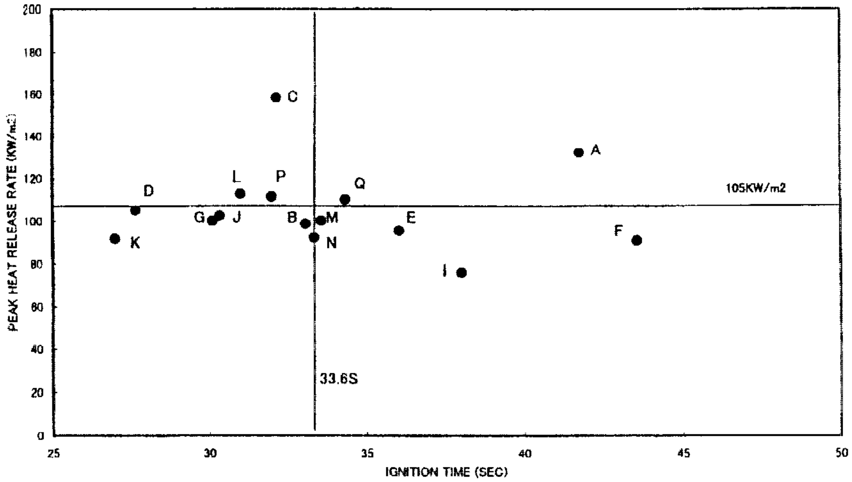

Figure 5(a) GB, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 5(b) GB, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

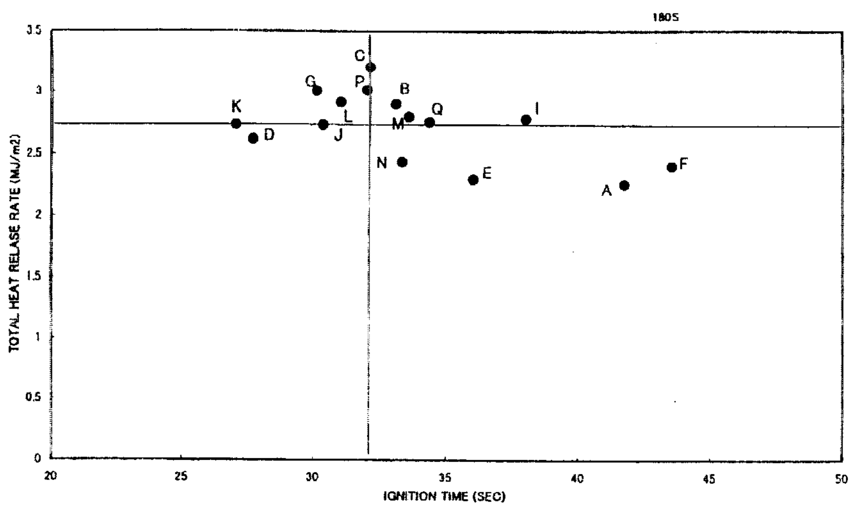

Figure 5(c) GB, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

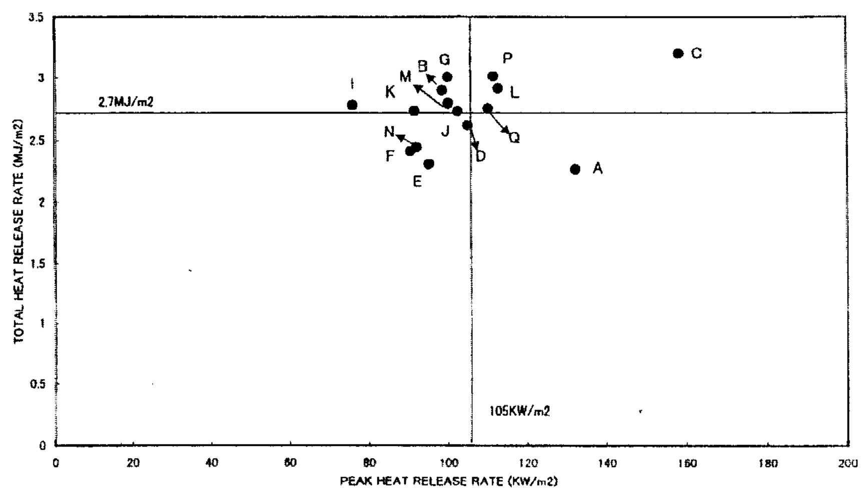

Figure 5(d) GB, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

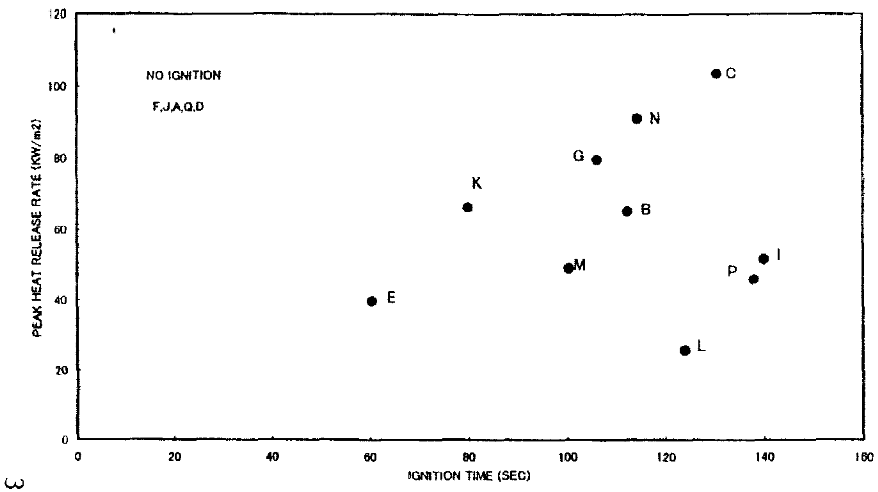

Figure 5(e) GB, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 5(f) GB, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

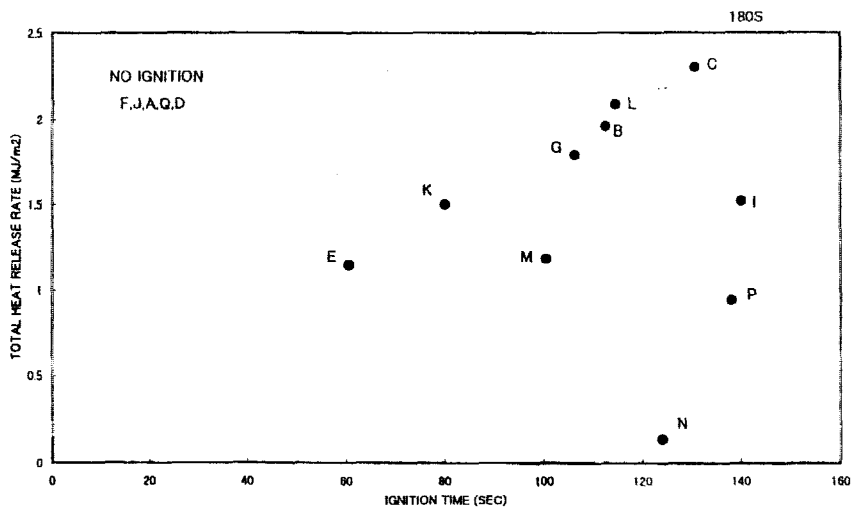

Figure 5(g) GB, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

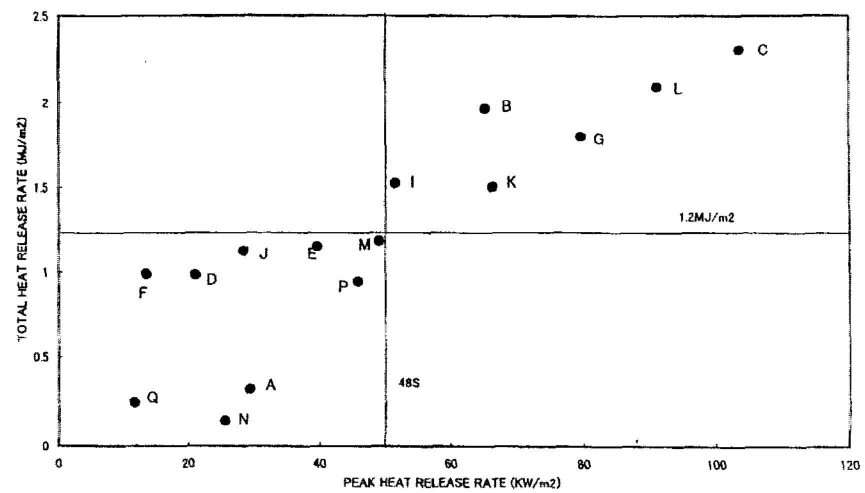

Figure 5(h) GB, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

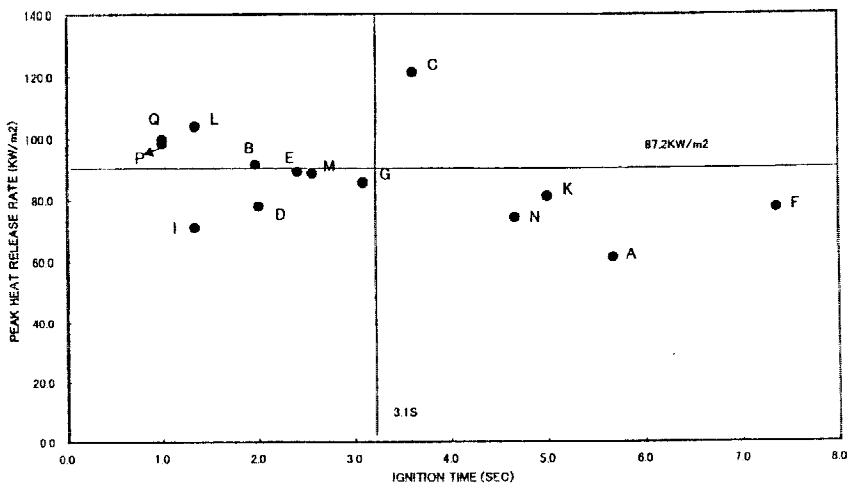

Figure 6(a) FGPC, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 6(b) FGPC, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

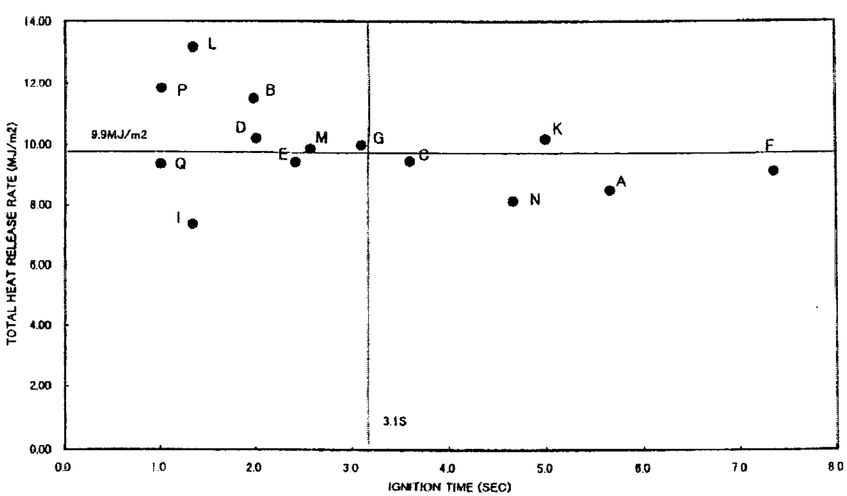

Figure 6(c) FGPC, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

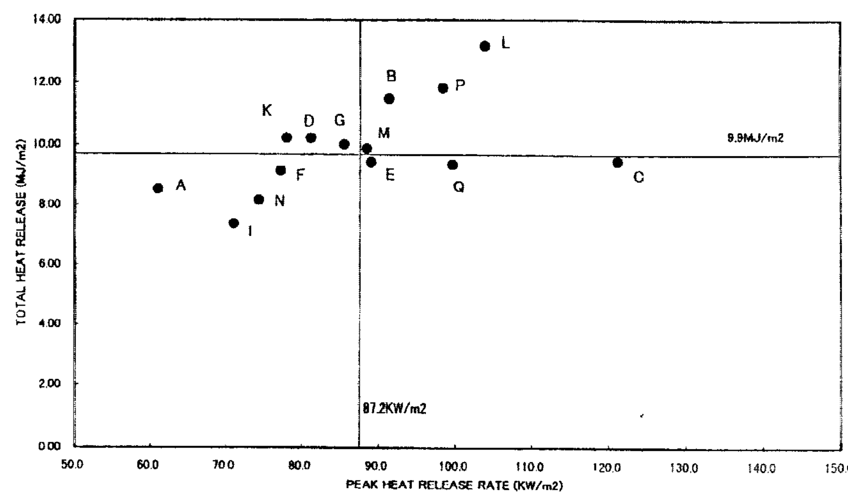

Figure 6(d) FGPC, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

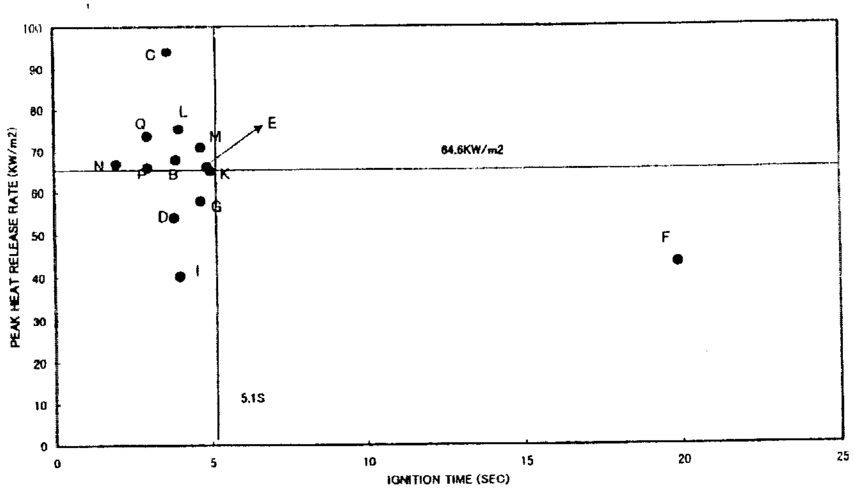

Figure 6(e) FGPC, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 6(f) FGPC, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

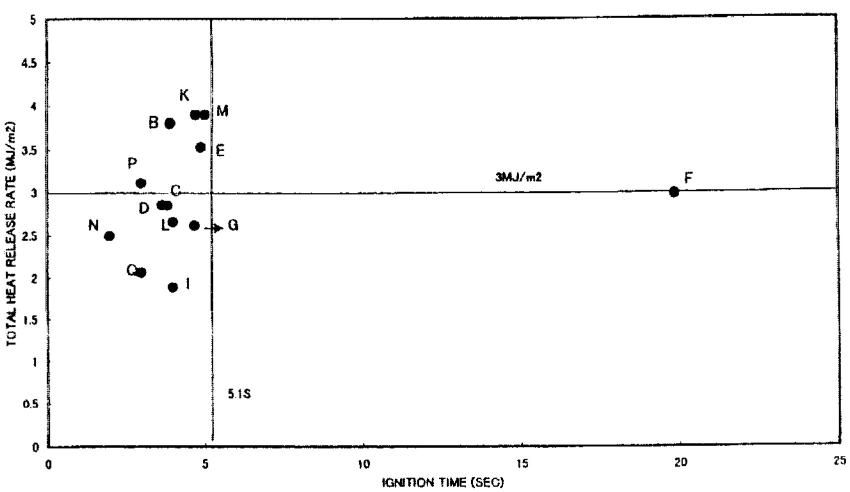

Figure 6(g) FGPC, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

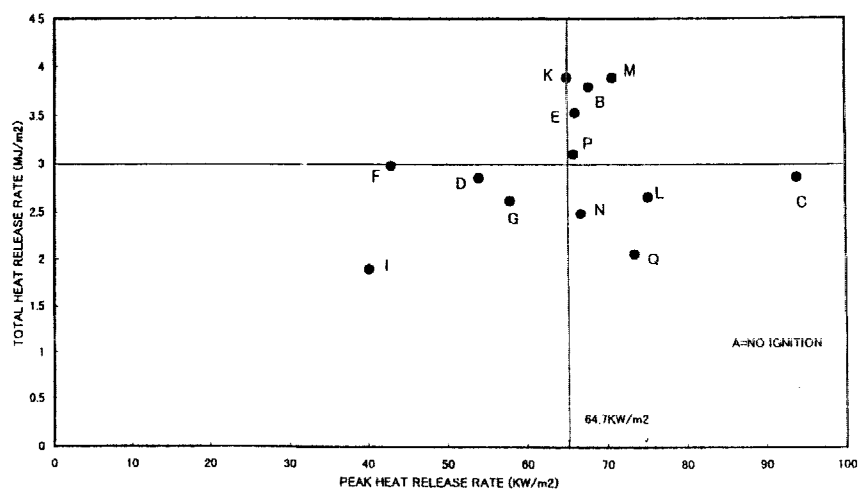

Figure 6(h) FGPC, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

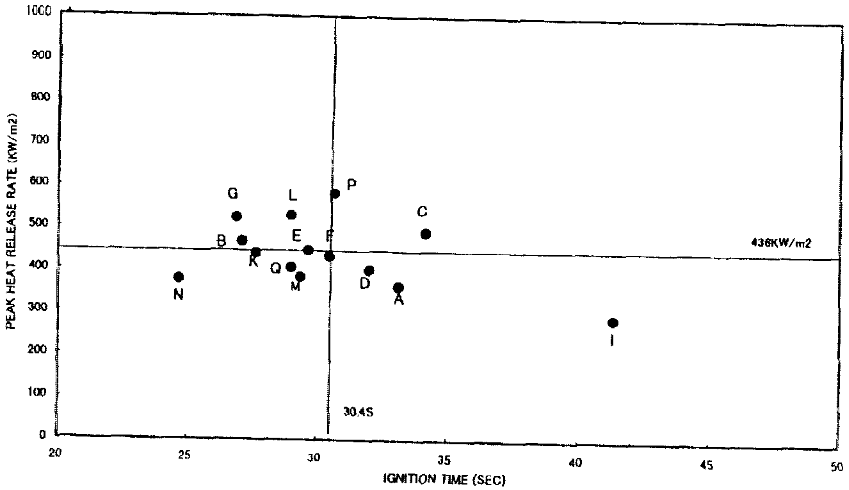

Figure 7(a) PS, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 7(b) PS, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

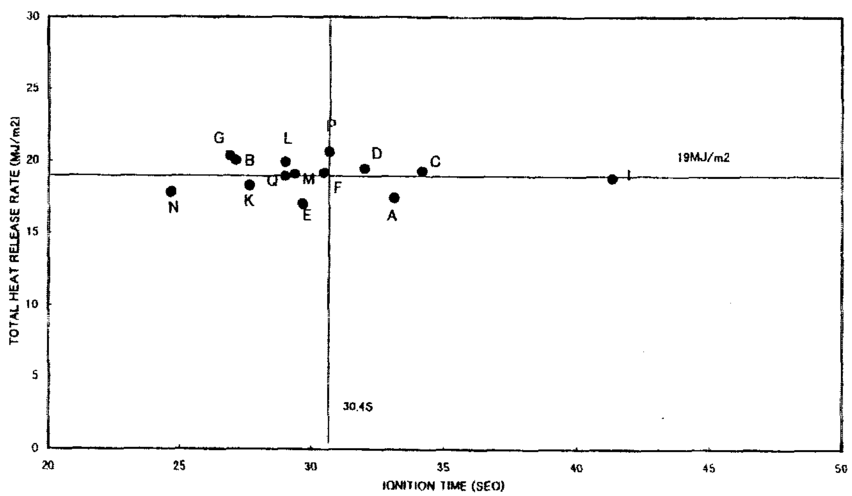

Figure 7(c) PS, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

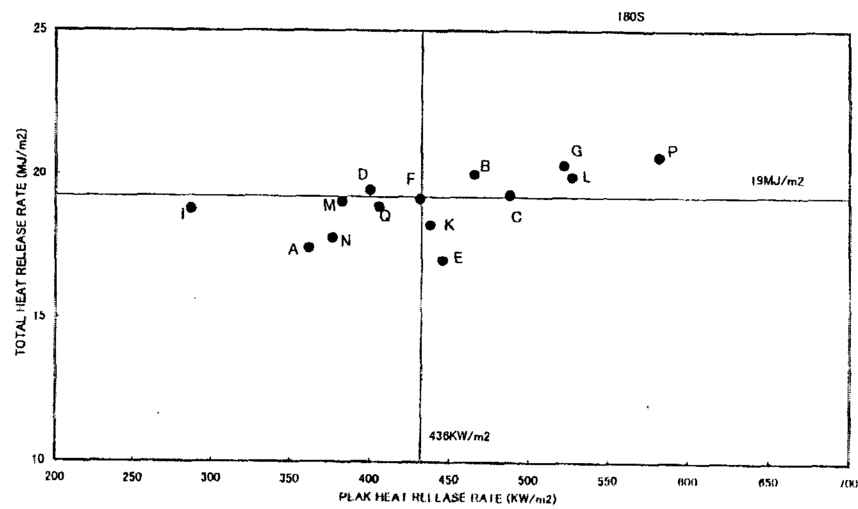

Figure 7(d) PS, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

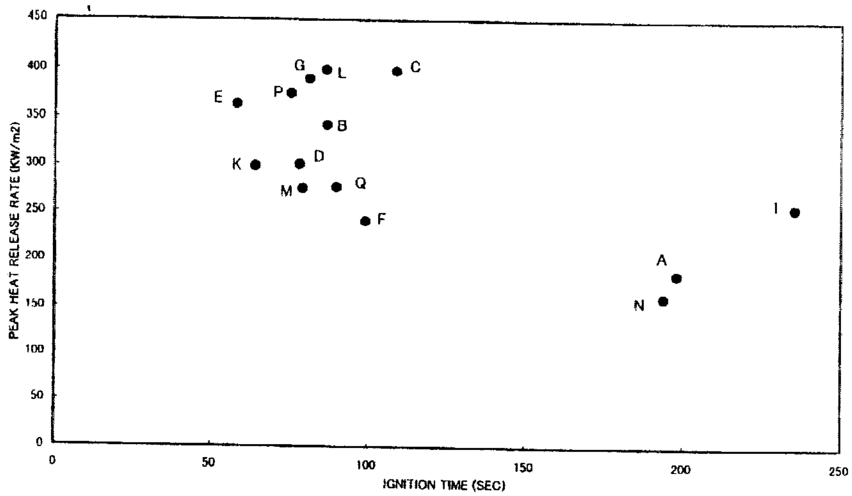

Figure 7(e) PS, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 7(f) PS, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

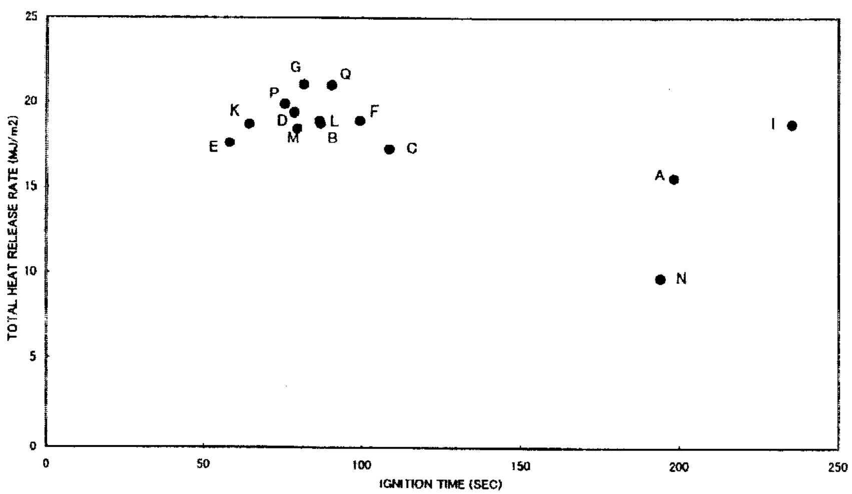

Figure 7(g) PS, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

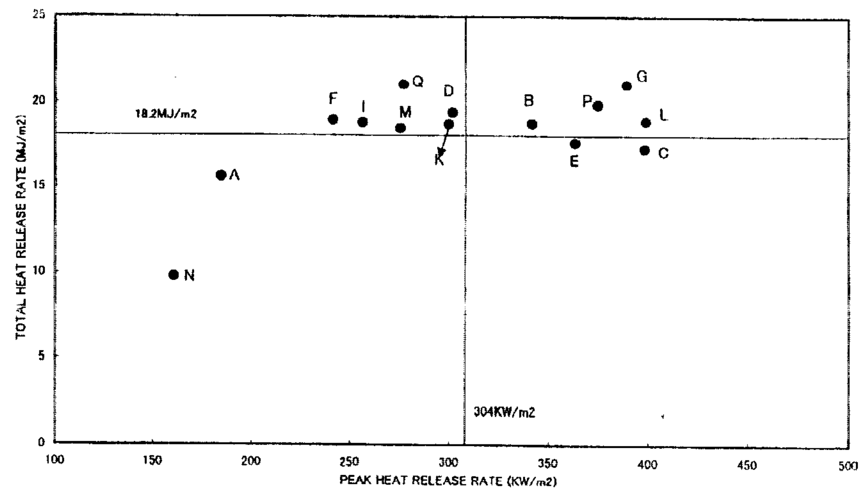

Figure 7(h) PS, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

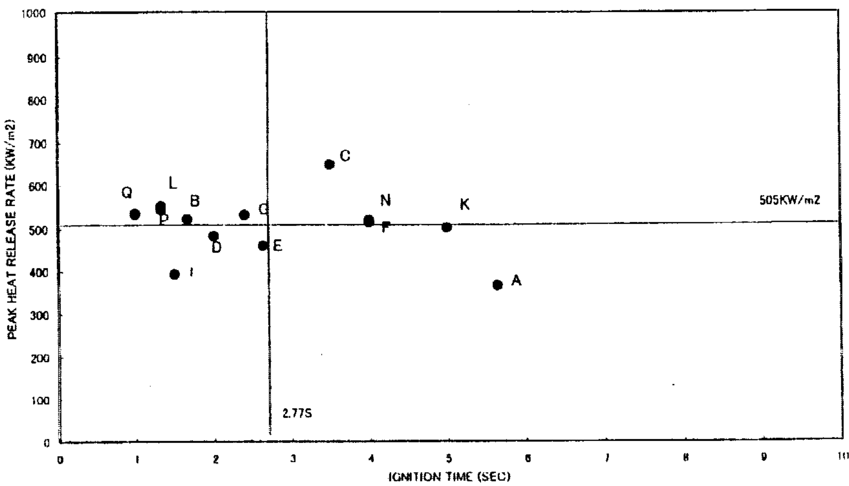

Figure 8(a) PU, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 8(b) PU, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

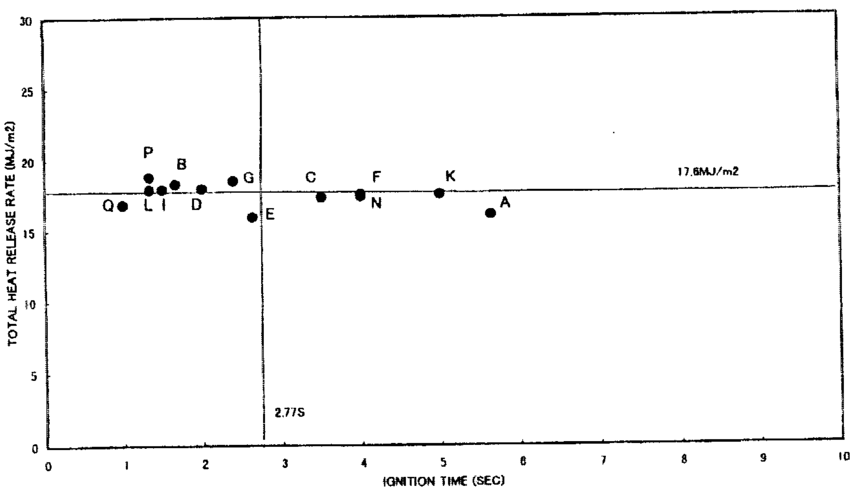

Figure 8(c) PU, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

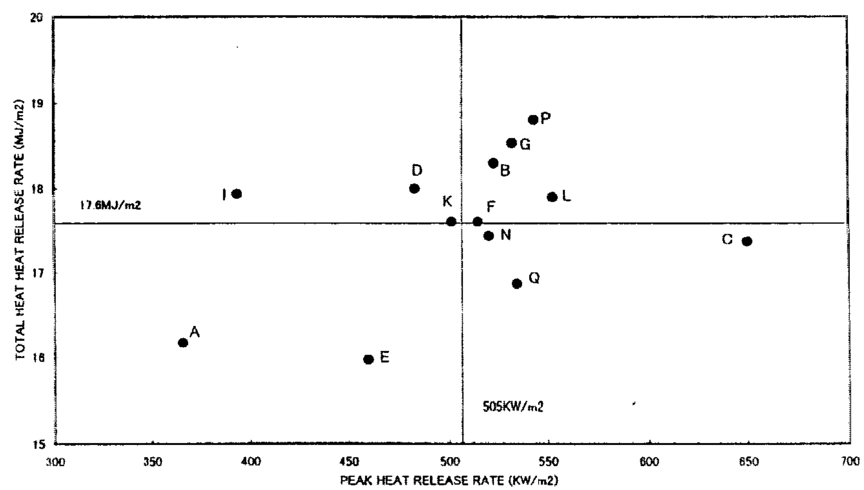

Figure 8(d) PU, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

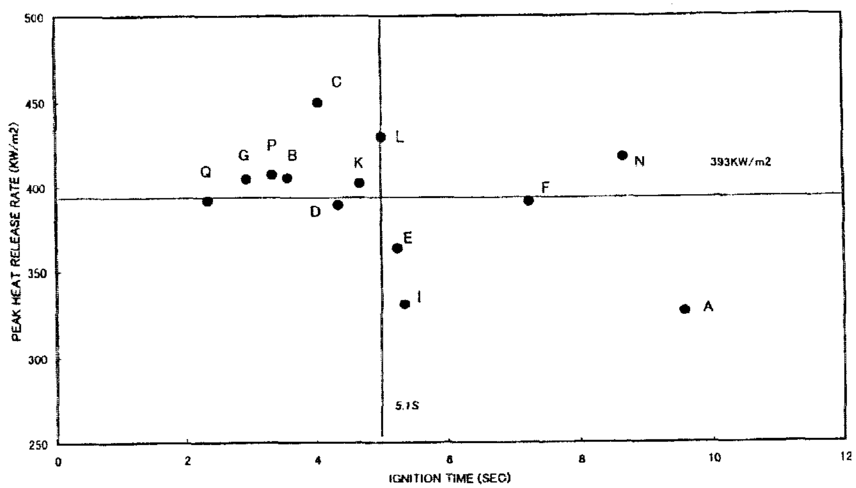

Figure 8(e) PU, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 8(f) PU, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

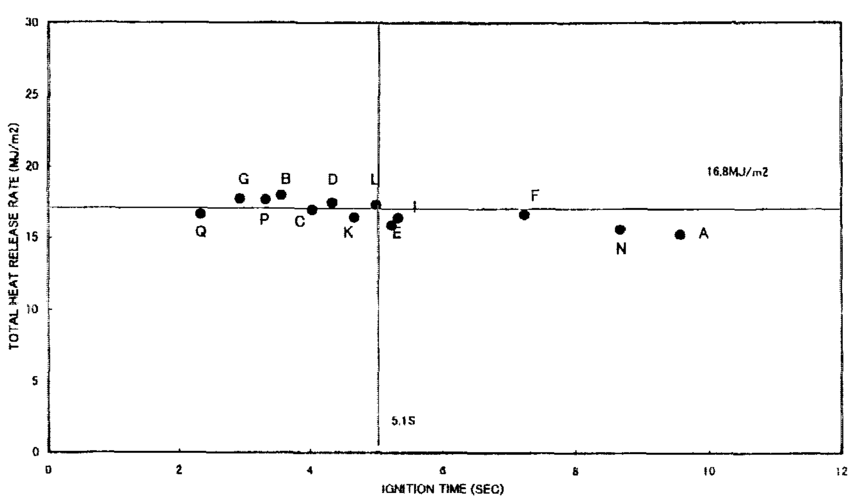

Figure 8(g) PU, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

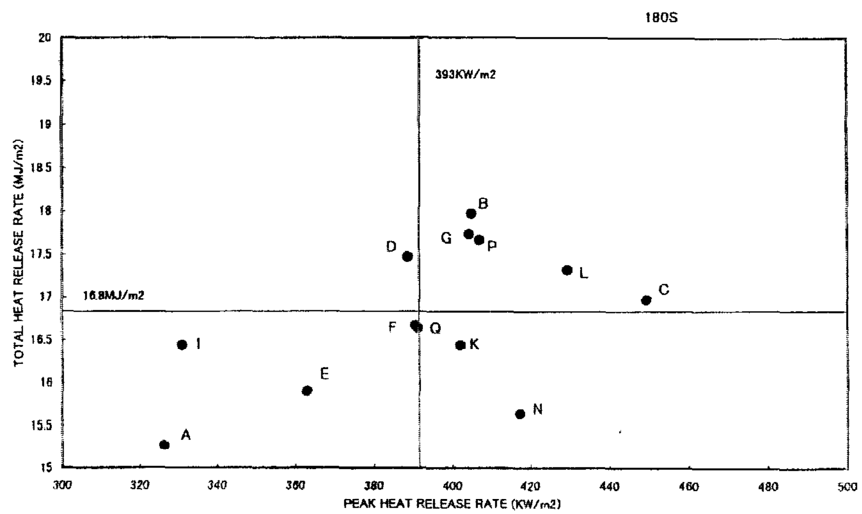

Figure 8(h) PU, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²